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Cost Optimisation Study for the SPL

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Abstract

A study of relative costs for the SPL (Superconducting Proton Linac) using the best system information available at the time is described in this report. The aim of the study was to determine the influence on SPL costs from the linac output energy and the beam pulse length. The costing model and the modular components for the linac were CERN specific, on the basis of cost savings to be realized from reusing LEP (Large Electron-Positron storage ring) components. A routine (SPL Cost Optimiser) was developed to investigate costs of SPL as a function of different parameters including pulse length, output energy, duty cycle and structure components.

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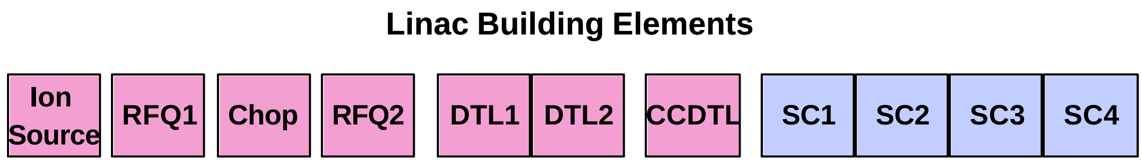
1. INTRODUCTION

Selection of system parameters for the SPL linac, designed as a proton injector for a Neutrino Factory, depends on requirements provided by the neutrino beam users and on expected performance. Details of a conceptual design for a 2.2 GeV linac injector with 4 MW of beam power operating at 75 Hz are given in Ref. [1]. Although Ref. [1] is an excellent design document, it only explains cost savings associated with reusing LEP components; it does not provide cost information that could justify some of the system parameter choices. Since issuing this report in 2000, an important parameter for the machine was changed; the pulse repetition rate was lowered to 50 Hz from 75 Hz, leading to other parameter changes. Work is finishing on the optimisation of this new conceptual design on the basis of the physics of the linac, as well as on mechanical constraints. This change opened an opportunity to investigate the effect of costs on several important parameters such as linac output energy and beam pulse length. Results of a cost optimisation investigation can then be used to assist in justifying the final choice of linac parameters. This report looks at the influence of several parameters in order to assist the choice of key linac parameters. Results of this investigation support a choice of 2.8 ms for the beam pulse length and a selection of an output energy near 2.2 GeV.

2. BASIC LINAC MODEL

Figure 1 gives a layout of the basic elements for the linac model studied in this report. Items with a blue background colour are based on superconducting (SC) technology while those with a rose background colour are based on room-temperature (NC, normal-conducting) technology. The linac model used in the optimisation calculations was quantized as described below to simplify calculations. Results based on a more detailed breakdown of the linac into smaller pieces would only provide second-order corrections to the results. The aim of the study was to determine the overall cost effect associated with parameter choices and not to look at smaller influences that can arise. Also, it was imperative to ensure that CERN-specific case constraints were used throughout this study. This local constraint meant it was important to utilize as much of the LEP hardware and technology as possible.

Only one ion source and one RFQ (Radio Frequency Quadrupole) architecture (RFQ1 and RFQ2 with a chopper system between) were considered in the model of the linac, as long as the peak pulsed beam current required from the ion source was less than 75 mA. Two similar lines would be used for currents in excess of 75 mA. Details for these front-end elements are found in Table I. The chopper system (Chop) has five rf cavities in addition to other components.



0.045	**3**	**3**	**7**	**12**	**18**	**120**	**237**	**389**	**1080**	**END**
Element Output Energy (MeV)										

Fig. 1: Basic building elements that comprise the SPL linac as defined in the text.

One fixed item in the investigation was the 4 MW beam-power requirement at 2.2 GeV. Data [2] on pion production per proton per GeV was used to normalize beam currents for other linac output energies. Another fixed item for all of the calculations within this model of the linac was the output transition energy from each element as shown in Fig. 1. The energies for the transitions between different elements never changed. This limitation on transition energies might be considered an inferior feature of the model, however this method allowed for a reasonable comparison of all parameters. Changes would have produced only second order effects in the cost results. Cost results presented here should be used only as indicating trends. Detailed calculations involving beam dynamics and mechanical constraints in the neighbourhood of the indicated optimum location should be used to determine an appropriate conceptual linac design.

Table I lists parameters of the complete linac model used in this report and Table II defines the SC unit elements in a little more detail. Most of the information in Table I comes from data or interpolations of the data in Ref. [1]. Following the RFQ-chopper-RFQ assembly were two NC DTL (Drift Tube Linac) tanks (DTL1 and DTL2) which increased the beam energy to 12 and 18 MeV respectively. Table I also lists the rf structure power required to establish the energy gains for the tank lengths listed.

Table I: Parameters used for the different elements of the SPL linac model used in the calculations.

Element	Ion Source Injector	RFQ1	Chopper	RFQ2	DTL1	DTL2	CCDTL	SC1	SC2	SC3	SC4
Output Energy (MeV)	0.045	3	3	7	12	18	120	237	389	1080	Final (2200)
Total Length (m)	3	3	6	4	4.1	5.1	69.6	101	80	153	(357)
Initial Unit Definition	One assembly	One coupled RFQ	Five cavities	One coupled RFQ	One tank assembly	One tank assembly	One tank per rf input	One cryostat	One cryostat	One cryostat	Three cryostats
Unit Active Length (m)	3	2.6	6	3.9	3.3	4.3	7.73	5.92	8.92	11.29	33.86
Unit Structure RF Power (MW)		0.33	0.3	0.46	0.64	0.84	0.66				
Maximum Gradient (MV/m)		2.5	2.5	2.5	2.5	2.5	2.5	3.5	5	9	7.5
Average Stable Phase (degrees)		-30		-30	-36	-32	-30	-25	-20	-15	-15
Average Transit Time Factor					0.75	0.75	0.75	2/p	2/p	2/p	2/p
Initial Number of Units	1	1	1	1	1	1	9	14	8	12	9
Number of RF Drives		1	5	1	1	1	9	42	32	12	18
RF Drives Power (MW)		1	0.1	1	1	1	1	0.1	0.1	1	1

Note that the DTLs were considered single tanks whose length was altered to fit accelerator requirements as described in Sec. 3. An average stable phase angle for each tank was utilized as was an average TTF (transit time factor). These two factors determined the electric field gradient in the cavity, a gradient checked to ensure that it did not exceed the maximum gradient value listed in the table. Following the DTLs was a nine-unit CCDTL that had a stable phase angle of -30^{o} and a TTF of 0.75, based on averaging Ref [1] details. As described in Sec. 3, if either gradient or rf requirements for the CCDTL exceeded limitations, then additional units were added to the system, quantized on a 7.73 m length with one 1 MW rf klystron driver.

After 120 MeV, beam acceleration was in one of four SC elements. Details are provided in Table II. The TTF for all the SC cavities was assumed to be $2/p$, the value for a standard pillbox cavity. These elements were quantized on the basis of one cryostat except for the final element, SC4, which was quantized on the basis of three cryostats driven by two rf drives (two 1 MW klystrons per three cryostats). Therefore SC4 utilized one klystron driver splitting the power between 6 cavities (24 cells), 4 cavities in one cryostat and 2 in an rf-split cryostat. SC3 was quantized with one 1 MW klystron driver feeding 4 cavities (20 cells) in one cryostat. SC2 was quantized on the basis of one cryostat with 4 cavities, each cavity driven by one 0.1 MW tetrode. Similarly, SC1 quantization had one cryostat with 3 cavities, each cavity driven by one 0.1 MW tetrode. If gradients and/or rf power exceeded limitations, additional quantized elements were added to the model for the particular output energy being considered.

Table II: Details of the four SC linac elements.

SC Linac Section	Cryostat Length (m)	Cavities per Cryostat	Cells per Cavity	Cell Beta
SC1	5.92	3	4	0.52
SC2	8.92	4	4	0.7
SC3	11.29	4	5	0.8
SC4	11.29	4	4	1

2.1 Cost model

Most of the background information used in the costing model was obtained from discussions with Maurizio Vretenar [3] on the basis of the 75 Hz study and estimates he obtained for various components, including conventional engineering. It must be emphasized that the costs given below are CERN specific and not firm estimates. However, the information is useful for investigating trends in costs. An explanation of some of the cost assumptions follows, including cost breakdowns developed for this study:

- The H^- source, RFQs and LEBT, and the chopper with high and low power electronics were assumed to cost 0.6, 6.0 and 3.5 M CHF, respectively, for a single beam line with a pulsed peak beam current less than 75 mA from the ion source. These values were independent of output proton energy.
- Transfer lines (vacuum, magnets, power supplies), dumps (two plus one and a half spares), controlled access and alarms, radiation monitoring, PS injection, ISOLDE injection, land acquisition, spare SC cavities for all betas, and cavity cold tests (three bunkers plus five years operation) were assumed to cost 4.0, 1.8, 1.3, 0.5, 4.0, 0.5, 1.5, 10 and 10 MCHF, respectively. These values were independent of output proton energy.
- Contingency on the whole project estimate was assumed to be 10%. Although rather low at this stage of the project, this 10% value might be reasonable on the basis of known components and available equipment from LEP.
- Control costs were assumed to be 10% of the cost of the project items, not including the contingency mentioned above. Again this is a rather low value but somewhat justified by available equipment and the fact that some of the work would be accomplished by in-house manpower.

An explanation of the more complex assumptions follows in Table III listing the variables, cost breakdown systematics and the analysis used in the model for determining costs. Total rf structure lengths varied from 700 to 1000 m, a difference not large enough to impact the assumptions.

Table III: Variables and assumptions used in the cost modelling.

Item	Comments
DTL1, DTL2	**Estimated using: COST (M CHF) = 0.5 + 0.35 x [Length of DTL (m)].**
CCDTL	**Estimated on the basis of the number of units: COST (M CHF) = 0.5 x [Number of CCDTL Units].**
Quads with Power Supplies	**Estimated using 10 M for the nine CCDTL system of the reference 75 Hz system (assumed this looked after DTL requirements as well): COST (M CHF) = (10 / 9) x [Number of CCDTL Units].**
Tetrode Amplifiers	**Estimated using number needed and 10 % spares: COST (M CHF) = 0.2525 x [Number plus 10 %].**
Klystron Amplifiers	**Estimated using 25 M for 44 units with spares of reference 75 Hz system. Numbers less than 44 costed on proportional basis: COST (M CHF) = (25 / 44) x [Number]. A premium for klystron amplifiers in excess of 44 used: COST (M CHF) = 25 + 1.615 x [Number - 44]. The 1.615 M per extra system is based on 2.5 / 6 M for power supply, 0.23 M for waveguides, etc., 0.4 M for the klystron and 25 / 44 M for pulsing systems including capacitor bank.**
Cavity Servos and Beam Phase Monitoring	**Estimated using number of rf drivers (tetrodes plus klystrons) relative to 122 total drivers at 3 M of the reference 75 Hz system: COST (M CHF) = (3 / 122) x [Total Number].**
SC4 *b* = 1.0	**Estimated using 27 LEP-based cryostat system cost of 4.8 M. Cryostat numbers to 44 costed on proportional basis: COST (M CHF) = (4.8 / 27) x [Number]. Above 44, premium cost per cryostat was 2 M.**
SC3 *b* = 0.8	**Estimated using number of LEP-based cryostats left from 44 total less the *b* = 1.0 requirements: COST (M CHF) = 0.6 x [Number of LEP] + 2 x [Number not LEP].**
SC2 *b* = 0.7	**Estimated using number of cryostats: COST (M CHF) = 2 x [Number].**
SC1 *b* = 0.52	**Estimated using 27 M for 14 cryostats: COST (M CHF) = (27 / 14) x [Number]**
Beam Instrumentation	**Estimated using 6.3 M estimate of the reference 75 Hz system on basis of accelerator length relative to 800 m of the reference 75 Hz system: COST (M CHF) = (6.3 / 800) x [Accelerator length (m)].**
Civil Engineering	**Estimated using base cost of 31.23 M (75.65 M minus 44.42 M for linac and klystron tunnels, etc. from the reference 75 Hz system) plus 25 % of the remaining 44.42 M. 75 % of 44.42 M allocated on basis of accelerator length relative to 800 m of the reference 75 Hz system: COST (M CHF) = (31.23 + 0.25 x 44.42) + 0.75 x (44.42 / 800) x [Accelerator Length (m)].**
Cooling and Ventilation	**Estimated using 95 % of 10.02 M estimate of the reference 75 Hz system as base cost, and remaining 5 % on basis of accelerator length relative to 800 m of the reference 75 Hz system: COST (M CHF) = 0.95 x 10.02 + 0.05 x (10.02 / 800) x [Accelerator length (m)].**
Electricity	**Estimated using 95 % of 14.627 M estimate of the reference 75 Hz system as base cost, and remaining 5 % on basis of accelerator length relative to 800 m of the reference 75 Hz system: COST (M CHF) = 0.95 x 14.627 + 0.05 x (14.627 / 800) x [Accelerator length (m)].**
Cryogen Plant	**Estimated using 34.5 M of the reference 75 Hz system as base cost and remaining 5 M of the reference 75 Hz system for warm piping and He transfer lines on basis of accelerator length relative to 800 m of the reference 75 Hz system: COST (M CHF) = 34.5 + (5 / 800) x [Accelerator length (m)].**
Vacuum	**Estimated using 8 M estimate of the reference 75 Hz system on basis of accelerator length relative to 800 m of the reference 75 Hz system: COST (M CHF) = (8 / 800) x [Accelerator length (m)].**

3. RF LINAC OPTIMISATION AND COST ANALYSIS

The initial linac model was based on the 75 Hz reference design [1] with average proton beam power of 4 MW on a target from a 2.2 GeV beam with 2.2 ms beam pulse length. This parameter set established the normalized beam power used for calculations described below, on the basis of pions produced per proton per GeV. Beam currents at 2.2 GeV and 50 Hz with a 2.8 ms pulse length were based on the same average beam power to the target as for the 75 Hz case. For a 2.8 ms pulse length at 50 Hz this meant that the average pulse current was increased to 13 mA from the 11 mA used for the 75 Hz design. Data [2] showed that pion production per proton per GeV for a pion energy range (80 MeV < E < 450 MeV) decreased by 6% from 2.2 GeV to 1.6 GeV and increased by 7.8% from 2.2 GeV to 2.8 GeV. This information was used to normalize beam powers required to produce the same number of useful pions for the linacs studied. The optimising routine ('SPL Cost Optimiser' listed in Appendix A) studied a set of linacs whose output energy varied from 1.6 GeV to 2.8 GeV in 0.2 GeV steps using information given in Sec. 2. In addition to an ability to change machine specifications and costing assumptions, repetition rate and pulse length were changed to examine the influence of these parameters on relative costs. For each linac output energy, characteristics of the beam pulse were determined as shown in Table IV for the 2.8 ms, 50 Hz case.

Independent of linac design, the study used a chopping efficiency of 60% on the basis of a 5 out of 8 pulse pattern for filling the ring, and a 140 bunch out of 146 pattern to allow for extraction kicker operation. Capture of beam from the ion source was assumed to be 85%. These two assumptions helped specify the parameters shown in the following table.

Table IV: Beam pulse characteristics for the 2.8 ms 50 Hz case.

Output Energy (GeV)	**1.6**	**1.8**	**2**	**2.2**	**2.4**	**2.6**	**2.8**
Relative Pion Production (Normalized at 2.2 GeV)	0.940	0.958	0.978	1.000	1.024	1.050	1.078
Average Beam Current in Pulse (mA)	19.0	16.6	14.6	13.0	11.6	10.5	9.5
Peak Beam Current in Pulse (mA)	31.7	27.6	24.3	21.6	19.4	17.4	15.8
Ion Source Output (mA)	37.3	32.5	28.6	25.5	22.8	20.5	18.6
Average Beam Power in Pulse (MW)	30.4	29.8	29.2	28.6	27.9	27.2	26.5
Beam Power [Normalized to Pion Production] (MW)	4.3	4.2	4.1	4.0	3.9	3.8	3.7

Based on these assumed beam values for a particular repetition rate and particular beam pulse length, linacs were designed for the energy region from 1.6 GeV to 2.8 GeV using the basic elements described in Table I. The length of the high energy section of the linac SC4 was determined using the output energy desired and the assumed SC4 energy gain per cryostat, within the quantization constraints for the number of cryostats of this element. To determine power available for each rf structure from the nominal-rated tubes at 0.1 MW for the tetrodes and 1.0 MW for the klystrons, rf margin factors of 0.75 and 0.8 were used for the SC and NC structures respectively. Hence, only 0.75 MW was available to a SC cavity from a 1.0 MW klystron drive. The rf margin factors allowed for control capability (tubes not run at full saturation), waveguide losses, coupling mismatches, circuit components and operation leverage. The lower value (0.75) was used for the SC structures because of experience indicating that a larger margin is required for control capability with respect to beam loading and Lorentz detuning. Some experts believe that the SC margin should be even lower, such as 0.7, but that was not considered a viable constraint for these studies. Unlike for the SC case, rf drive for the NC elements provided rf power for structure losses in establishing accelerating fields as well as for the beam. Adequate rf rise time was allowed, as described later to permit establishing the required fields in the SC elements.

On the basis of this first iteration for the different output energy linac designs, gradients were checked to ensure that none of the elements had on-axis electric-field gradients exceeding maximum values listed in Table I. Values listed in Table I for TTF and stable phase angle were used to determine operating gradients in MV/m using the assumed energy gains per unit length. In addition, each SC cryostat was assumed to have only 80% of useful cavity length for beam acceleration; the rest of the cryostat length was required for interconnections, shielding, coupling ports and end pipes. For those cases in which the gradient was exceeded, the element was made longer using quantization lengths discussed above. In the few cases where the element could be made shorter, this was allowed within the constraints of allowable gradient. For the NC DTLs, the simple relationship of [structure power times length is a constant] was used to determine the new length of the element. New designs were then created for the different energy linacs and these designs were checked to ensure that rf power was not exceeded for each unit of the elements, based on available power to each rf structure. For those cases that exceeded rf power availability, the element was made longer using the methods described above for the gradient checks. In this manner, designs meeting gradient and rf constraints were determined within the constraints of element quantization and fixed energy transition regions.

Using the iterated designs for the linacs at a particular repetition rate and beam pulse length, the lengths of the linacs were determined using the actual physical lengths of the structures, allowing for interconnections, beam diagnostics, monitors and couplings. AC power requirements to drive the rf systems described above were determined using a 60% conversion efficiency for rf power generation (tubes are not operated at full saturation), 90% efficiency for AC to DC conversion and power supply losses, and the following filling rise times for the different elements in order to determine the rf pulse length (beam pulse time plus filling rise time). RF filling times for the different elements of the linacs were assumed to be 0.1 ms for all of the NC structures, 0.9 ms for SC1 and SC4, 1.13 ms for SC2 and 1.36 ms for SC3. Many experts might consider the 60% value used for tube efficiencies too high for the particular operation under study; 50-55% might be more acceptable. This value of 60% was used on the assumption that efforts would be made in the future to improve operation characteristics. The value selected does not impact linac costs, but does impact AC costs associated with operation of a facility employing such a linac in the future.

4. EXAMPLES FOR 50 HZ AND 75 HZ

Calculations for linacs within the design constraints listed above and using the parameters discussed are given in Tables V and VI for the 2.8 ms, 50 Hz case and the 2.2 ms, 75 Hz case, respectively. Total rf power in MW for each element and rf power per drive unit are listed in the left-hand side of the tables. Maximum values of 1.0 MW and 0.1 MW were never exceeded for the klystrons and the tetrodes, respectively. The right-hand side of the tables show either the number of components for each element or the component length, as well as the gradient for the particular unit in MV/m. In addition, the bottom of the tables provides summaries on the total amount of rf in MW required from the tubes, the number of 1.0 MW klystrons, the number of 0.1 MW tetrodes, the number of LEP-based cryostats and the length of the accelerator. A simple check on the validity of the model is that the rf structure length of the linac for the 75 Hz case with 2.2 ms beam pulse length is 802 m, to be compared with the equivalent 786 m in Ref. [1], a linac design that had two less SC3 cryostats, one more SC1 cryostat and a DTL2 that was 0.6 m shorter, all of which account for the difference in length. Element numbers are different than those used in Ref [1] mainly because of gradient and power limitations imposed by rf delivery constraints.

Table V: Summary of parameters for optimised design cases with a 2.8 ms 50 Hz choice.

Linac Output Energy	1.6	1.8	2	2.2	2.4	2.6	2.8		1.6	1.8	2	2.2	2.4	2.6	2.8	
RF Power to SC4 (MW)	13.178	15.910	17.919	19.394	20.462	21.213	21.714		21	24	27	30	33	39	42	**No. of Cryostats**
Power/Unit	0.941	0.994	0.996	0.970	0.930	0.816	0.775		4.46	5.40	6.14	6.72	7.21	7.02	7.38	**Gradient (MV/m)**
RF Power to SC3 (MW)	17.511	15.269	13.459	11.965	10.711	9.643	8.723		18	16	14	14	14	14	14	**No. of Cryostats**
Power/Unit	0.973	0.954	0.961	0.855	0.765	0.689	0.623		6.91	7.78	8.89	8.89	8.89	8.89	8.89	**Gradient (MV/m)**
RF Power to SC2 (MW)	3.852	3.359	2.961	2.632	2.356	2.121	1.919		10	9	8	8	8	8	8	**No. of Cryostats**
Power/Unit	0.096	0.093	0.093	0.082	0.074	0.066	0.060		3.56	3.96	4.45	4.45	4.45	4.45	4.45	**Gradient (MV/m)**
RF Power to SC1 (MW)	2.965	2.585	2.279	2.026	1.814	1.633	1.477		13	13	13	13	13	13	13	**No. of Cryostats**
Power/Unit	0.076	0.066	0.058	0.052	0.047	0.042	0.038		3.29	3.29	3.29	3.29	3.29	3.29	3.29	**Gradient (MV/m)**
RF Power to CCDTL (MW)	9.149	8.838	8.588	8.381	8.955	8.807	8.680		10	10	10	10	9	9	9	**No. of Units**
Power/Unit	0.915	0.884	0.859	0.838	0.995	0.979	0.964		2.03	2.03	2.03	2.03	2.26	2.26	2.26	**Gradient (MV/m)**
RF Power to DTL2 (MW)	0.989	0.987	0.985	0.984	0.984	0.983	0.983		5.33	5.23	5.15	5.09	5.03	4.99	4.95	**Length (m)**
Power/Unit	0.989	0.987	0.985	0.984	0.984	0.983	0.983		1.77	1.80	1.83	1.85	1.87	1.89	1.91	**Gradient (MV/m)**
RF Power to DTL1 (MW)	0.918	0.903	0.891	0.881	0.872	0.865	0.859		3.3	3.3	3.3	3.3	3.3	3.3	3.3	**Length (m)**
Power/Unit	0.918	0.903	0.891	0.881	0.872	0.865	0.859		2.50	2.50	2.50	2.50	2.50	2.50	2.50	**Gradient (MV/m)**
RF Power to RFQ2 (MW)	0.665	0.653	0.643	0.635	0.628	0.622	0.617		3.9	3.9	3.9	3.9	3.9	3.9	3.9	**Length (m)**
Power/Unit	0.665	0.653	0.643	0.635	0.628	0.622	0.617		1.58	1.58	1.58	1.58	1.58	1.58	1.58	**Gradient (MV/m)**
RF Power to Chopper	0.375	0.375	0.375	0.375	0.375	0.375	0.375		6	6	6	6	6	6	6	**Length (m)**
RF Power to RFQ1 (MW)	0.480	0.471	0.463	0.457	0.452	0.448	0.444		2.6	2.6	2.6	2.6	2.6	2.6	2.6	**Length (m)**
Power/Unit	0.480	0.471	0.463	0.457	0.452	0.448	0.444		1.75	1.75	1.75	1.75	1.75	1.75	1.75	**Gradient (MV/m)**
Total RF (MW)	50.1	49.3	48.6	47.7	47.6	46.7	45.8									
No. of 1 MW Klystrons	46	46	46	48	49	53	55						**Repetition Rate**	**50**	Hz	
No. of 0.1 MW Tetrodes	84	80	76	76	76	76	76						**Beam Pulse Length**	**2.8**	ms	
No. of LEP Cryostats	39	40	41	44	47	53	56									
Length (m)	**802**	**806**	**810**	**849**	**881**	**961**	**1000**									

Although the highest energy linac of Table V does not use rf power as efficiently as other linac designs, this does not have a significant impact on cost trends. Note that linacs with energies in excess of 2.2 GeV require more LEP-based cryostats than the 44 available.

Table VI: Summary of parameters for optimised design cases with a 2.2 ms 75 Hz choice.

Linac Output Energy	1.6	1.8	2	2.2	2.4	2.6	2.8		1.6	1.8	2	2.2	2.4	2.6	2.8	
RF Power to SC4 (MW)	11.181	13.499	15.204	16.455	17.361	17.999	18.424		18	21	24	27	33	39	42	**No. of Cryostats**
Power/Unit	0.932	0.964	0.950	0.914	0.789	0.692	0.658		5.20	6.18	6.90	7.47	7.21	7.02	7.38	**Gradient (MV/m)**
RF Power to SC3 (MW)	14.858	12.956	11.420	10.152	9.088	8.182	7.402		15	14	14	14	14	14	14	**No. of Cryostats**
Power/Unit	0.991	0.925	0.816	0.725	0.649	0.584	0.529		8.30	8.89	8.89	8.89	8.89	8.89	8.89	**Gradient (MV/m)**
RF Power to SC2 (MW)	3.268	2.850	2.512	2.233	1.999	1.800	1.628		9	8	8	8	8	8	8	**No. of Cryostats**
Power/Unit	0.091	0.089	0.079	0.070	0.062	0.056	0.051		3.96	4.45	4.45	4.45	4.45	4.45	4.45	**Gradient (MV/m)**
RF Power to SC1 (MW)	2.516	2.194	1.934	1.719	1.539	1.385	1.253		13	13	13	13	13	13	13	**No. of Cryostats**
Power/Unit	0.065	0.056	0.050	0.044	0.039	0.036	0.032		3.29	3.29	3.29	3.29	3.29	3.29	3.29	**Gradient (MV/m)**
RF Power to CCDTL (MW)	8.781	8.518	8.306	8.877	8.730	8.605	8.497		10	10	10	9	9	9	9	**No. of Units**
Power/Unit	0.878	0.852	0.831	0.986	0.970	0.956	0.944		2.03	2.03	2.03	2.26	2.26	2.26	2.26	**Gradient (MV/m)**
RF Power to DTL2 (MW)	0.986	0.985	0.984	0.983	0.983	0.983	0.983		5.21	5.13	5.06	5.01	4.96	4.92	4.89	**Length (m)**
Power/Unit	0.986	0.985	0.984	0.983	0.983	0.983	0.983		1.81	1.84	1.86	1.88	1.90	1.92	1.93	**Gradient (MV/m)**
RF Power to DTL1 (MW)	0.900	0.888	0.877	0.869	0.861	0.855	0.850		3.3	3.3	3.3	3.3	3.3	3.3	3.3	**Length (m)**
Power/Unit	0.900	0.888	0.877	0.869	0.861	0.855	0.850		2.50	2.50	2.50	2.50	2.50	2.50	2.50	**Gradient (MV/m)**
RF Power to RFQ2 (MW)	0.651	0.640	0.632	0.625	0.619	0.614	0.610		3.9	3.9	3.9	3.9	3.9	3.9	3.9	**Length (m)**
Power/Unit	0.651	0.640	0.632	0.625	0.619	0.614	0.610		1.58	1.58	1.58	1.58	1.58	1.58	1.58	**Gradient (MV/m)**
RF Power to Chopper	0.375	0.375	0.375	0.375	0.375	0.375	0.375		6	6	6	6	6	6	6	**Length (m)**
RF Power to RFQ1 (MW)	0.469	0.461	0.455	0.450	0.446	0.442	0.439		2.6	2.6	2.6	2.6	2.6	2.6	2.6	**Length (m)**
Power/Unit	0.469	0.461	0.455	0.450	0.446	0.442	0.439		1.75	1.75	1.75	1.75	1.75	1.75	1.75	**Gradient (MV/m)**
Total RF (MW)	44.0	43.4	42.7	42.7	42.0	41.2	40.5									
No. of 1 MW Klystrons	41	42	44	45	49	53	55						**Repetition Rate**	**75**	Hz	
No. of 0.1 MW Tetrodes	80	76	76	76	76	76	76						**Beam Pulse Length**	**2.2**	ms	
No. of LEP Cryostats	33	35	38	41	47	53	56									
Length (m)	**714**	**730**	**770**	**802**	**881**	**960**	**1000**									

To show the effects of gradients and rf power limitations, an extreme case with 3.4 ms beam pulse length at 50 Hz was investigated to look at effects of low beam loading. The results of these calculations are shown in Table VII. Note that at high output energies with low beam currents, the structures are limited by gradient and not by rf power constraints. Some savings in cost could be realized by having one rf driver feed more cavities than in the architecture used for this study. However, one 1.0 MW klystron driving six cavities is enough of a challenging development activity, with no guarantee of acceptable results. Increasing this drive scenario to eight per klystron would reduce costs by about 13 M CHF for the 2.4 GeV to 2.8 GeV cases, but not change the general shape of the cost trends. Results for the other beam pulse extreme, 2.4 ms, showed that rf power limitations completely dominated design, with cavity gradients well below maximum values.

Table VII: Summary of parameters for optimised design cases with a 3.6 ms 50 Hz choice.

Linac Output Energy	1.6	1.8	2	2.2	2.4	2.6	2.8		1.6	1.8	2	2.2	2.4	2.6	2.8	
RF Power to SC4 (MW)	10.249	12.374	13.937	15.084	15.915	16.499	16.889		18	21	24	27	33	39	42	No. of Cryostats
Power/Unit	0.854	0.884	0.871	0.838	0.723	0.635	0.603		5.20	6.18	6.90	7.47	7.21	7.02	7.38	Gradient (MV/m)
RF Power to SC3 (MW)	13.620	11.876	10.468	9.306	8.331	7.500	6.785		14	14	14	14	14	14	14	No. of Cryostats
Power/Unit	0.973	0.848	0.748	0.665	0.595	0.536	0.485		8.89	8.89	8.89	8.89	8.89	8.89	8.89	Gradient (MV/m)
RF Power to SC2 (MW)	2.996	2.612	2.303	2.047	1.833	1.650	1.492		8	8	8	8	8	8	8	No. of Cryostats
Power/Unit	0.094	0.082	0.072	0.064	0.057	0.052	0.047		4.45	4.45	4.45	4.45	4.45	4.45	4.45	Gradient (MV/m)
RF Power to SC1 (MW)	2.306	2.011	1.772	1.576	1.411	1.270	1.149		13	13	13	13	13	13	13	No. of Cryostats
Power/Unit	0.059	0.052	0.045	0.040	0.036	0.033	0.029		3.29	3.29	3.29	3.29	3.29	3.29	3.29	Gradient (MV/m)
RF Power to CCDTL (MW)	8.610	8.369	8.921	8.760	8.625	8.510	8.411		10	10	9	9	9	9	9	No. of Units
Power/Unit	0.861	0.837	0.991	0.973	0.958	0.946	0.935		2.03	2.03	2.26	2.26	2.26	2.26	2.26	Gradient (MV/m)
RF Power to DTL2 (MW)	0.985	0.984	0.984	0.983	0.983	0.983	0.983		5.16	5.08	5.02	4.97	4.93	4.89	4.86	Length (m)
Power/Unit	0.985	0.984	0.984	0.983	0.983	0.983	0.983		1.83	1.86	1.88	1.90	1.91	1.93	1.94	Gradient (MV/m)
RF Power to DTL1 (MW)	0.892	0.880	0.871	0.863	0.856	0.851	0.846		3.3	3.3	3.3	3.3	3.3	3.3	3.3	Length (m)
Power/Unit	0.892	0.880	0.871	0.863	0.856	0.851	0.846		2.50	2.50	2.50	2.50	2.50	2.50	2.50	Gradient (MV/m)
RF Power to RFQ2 (MW)	0.644	0.634	0.627	0.621	0.615	0.611	0.607		3.9	3.9	3.9	3.9	3.9	3.9	3.9	Length (m)
Power/Unit	0.644	0.634	0.627	0.621	0.615	0.611	0.607		1.58	1.58	1.58	1.58	1.58	1.58	1.58	Gradient (MV/m)
RF Power to Chopper	0.375	0.375	0.375	0.375	0.375	0.375	0.375		6	6	6	6	6	6	6	Length (m)
RF Power to RFQ1 (MW)	0.464	0.457	0.451	0.447	0.443	0.439	0.437		2.6	2.6	2.6	2.6	2.6	2.6	2.6	Length (m)
Power/Unit	0.464	0.457	0.451	0.447	0.443	0.439	0.437		1.75	1.75	1.75	1.75	1.75	1.75	1.75	Gradient (MV/m)
Total RF (MW)	41.1	40.6	40.7	40.1	39.4	38.7	38.0									
No. of 1 MW Klystrons	40	42	43	45	49	53	55						Repetition Rate	50	Hz	
No. of 0.1 MW Tetrodes	76	76	76	76	76	76	76						Beam Pulse Length	3.6	ms	
No. of LEP Cryostats	32	35	38	41	47	53	56									
Length (m)	**691**	**730**	**762**	**802**	**881**	**960**	**1000**									

Cost data are summarized in Table VIII for a 2.8 ms 50 Hz case using the assumptions and constraints listed above. As expected, the two items having the biggest impact on costs are the klystron amplifiers and the civil engineering.

Table VIII: Summary of costs for optimised design cases with a 2.8 ms 50 Hz choice.

Linac Output Energy (GeV)	1.6	1.8	2	2.2	2.4	2.6	2.8
H- Source	0.6	0.6	0.6	0.6	0.6	0.6	0.6
RFQs & LEBT	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Chopper with high and low power electronics	3.5	3.5	3.5	3.5	3.5	3.5	3.5
DTL	4.1	4.0	4.0	4.0	4.0	4.0	3.9
CCDTL	5.0	5.0	5.0	5.0	4.5	4.5	4.5
Quads with power supplies	11.1	11.1	11.1	11.1	10.0	10.0	10.0
Tetrode amplifiers (+spares)	23.3	22.2	21.1	21.1	21.1	21.1	21.1
Klystron Amplifiers (+ new klystrons)	28.2	28.2	28.2	31.5	33.1	39.5	42.8
Cavities servos and beam phase monitoring	3.2	3.1	3.0	3.0	3.1	3.2	3.2
Spare cavities (all betas)	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Beta=1.0 SC4 cavities	3.7	4.3	4.8	5.3	5.9	6.9	7.5
Beta=0.8 SC3 cavities	10.8	9.6	8.4	8.4	12.6	21.0	25.2
Beta=0.7 SC2 cavities	20.0	18.0	16.0	16.0	16.0	16.0	16.0
Beta=0.52 SC1 cavities	25.1	25.1	25.1	25.1	25.1	25.1	25.1
Beam instrumentation	6.3	6.3	6.4	6.7	6.9	7.6	7.9
Controls	33.2	32.9	32.5	33.2	33.9	36.0	37.1
Civil Engineering	75.7	75.9	76.1	77.7	79.0	82.3	84.0
Cooling and ventilation	10.0	10.0	10.0	10.1	10.1	10.1	10.1
Controlled access and alarm	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Electricity	14.6	14.6	14.6	14.7	14.7	14.8	14.8
Cryogen plant	39.5	39.5	39.6	39.8	40.0	40.5	40.8
Vacuum	8.0	8.1	8.1	8.5	8.8	9.6	10.0
Transfer lines (vacuum, magnets, power supplies)	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Dumps (2 + 1.5 spare)	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Radiation Monitoring	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Injection in the PS	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Injection in the ISOLDE	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Land Acquisition	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Cavities cold test (3 bunkers + 5 years duration)	10.0	10.0	10.0	10.0	10.0	10.0	10.0
10% Contingency	36.6	36.2	35.8	36.5	37.2	39.6	40.8
Total	**402.3**	**397.9**	**393.5**	**401.3**	**409.6**	**435.4**	**448.3**

Items that changed by more than 10% in a positive sense as the linac energy increased were controls, vacuum, beam instrumentation, SC3 and SC4. This trend was expected. Not expected was the decrease by more than 10% for CCDTL and SC2, a situation based on the beam power limitations on available power to establish fields in those elements. At first glance, the costs for the SC3 elements may seem incorrect. However, the extreme increase in costs was based on the fact that fewer LEP-based cryostats were available for linac designs above 2.2 GeV because they were required for the SC4 elements, and the number available for SC3 was more limited as the energy increased to 2.8 GeV.

A summary of the cost data obtained for design cases with different beam pulse lengths at 50 Hz is shown in Fig. 2. Notice that the optimum design is around 2 GeV with a pulse length of 2.8 ms. The difference in cost for the 2.2 GeV case relative to the 2.0 GeV case is only 6 M CHF, a value that does not override design selection criteria based on injection energy effects for the following ring. Also note that there seems to be no cost advantage for making the beam pulse length greater than 2.8 ms.

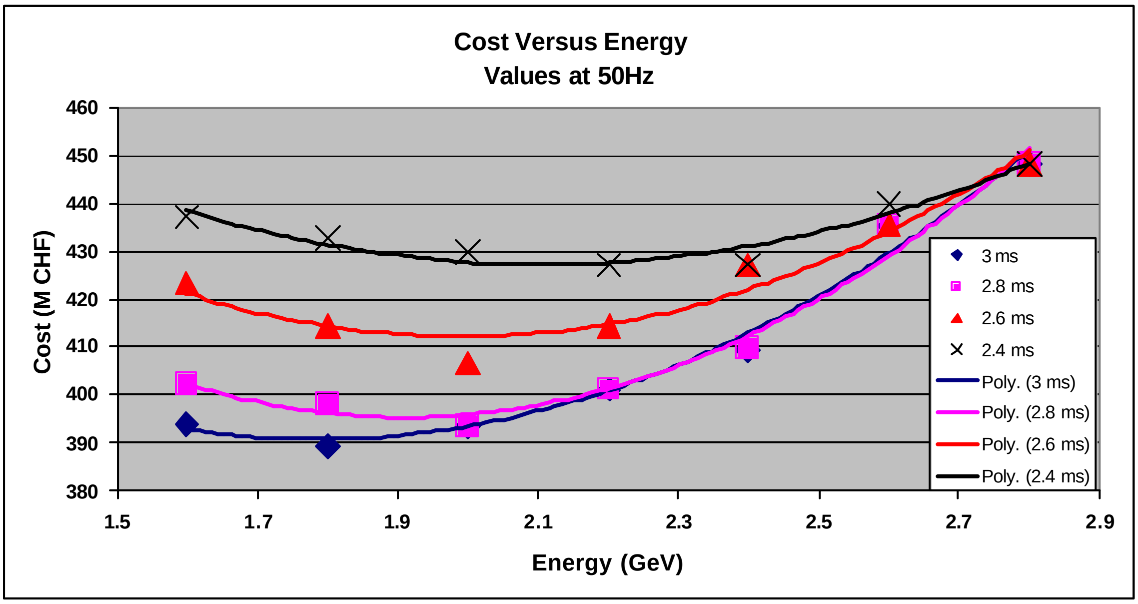


Fig. 2: Results of the cost optimisation studies for different beam pulse lengths at 50 Hz operation. Accelerator costs in M CHF are shown as a function of linac output energy. Note the optimum in costs around 2 GeV and that there is a penalty in costs for pulse lengths shorter than 2.8 ms.

Figure 3 gives a summary of the cost data for 75 Hz operation. These results indicate that an optimum energy for 75 Hz operation is around 1.8 GeV, a lower energy than for the 50 Hz case because of effects associated with less beam current in the pulse. For this 75 Hz case it is obvious that there is no advantage in having the pulse less than 2.2 ms, because of the increase in costs.

Figure 4 shows 50 Hz accelerator costs relative to pulse lengths from 2.4 to 3.6 ms for linac energies of 1.8, 2.0 and 2.2 GeV. Note that there is a shoulder around 2.8 ms, above which there is no cost advantage for the linac design. Below 2.8 ms there is a large cost penalty for the linac design which is about 80 M CHF per ms decrease of beam pulse length. Similar results for the 75 Hz case show a shoulder around 2.2 ms with a penalty for shorter pulse lengths of about 60 M CHF per ms decrease of beam pulse length.

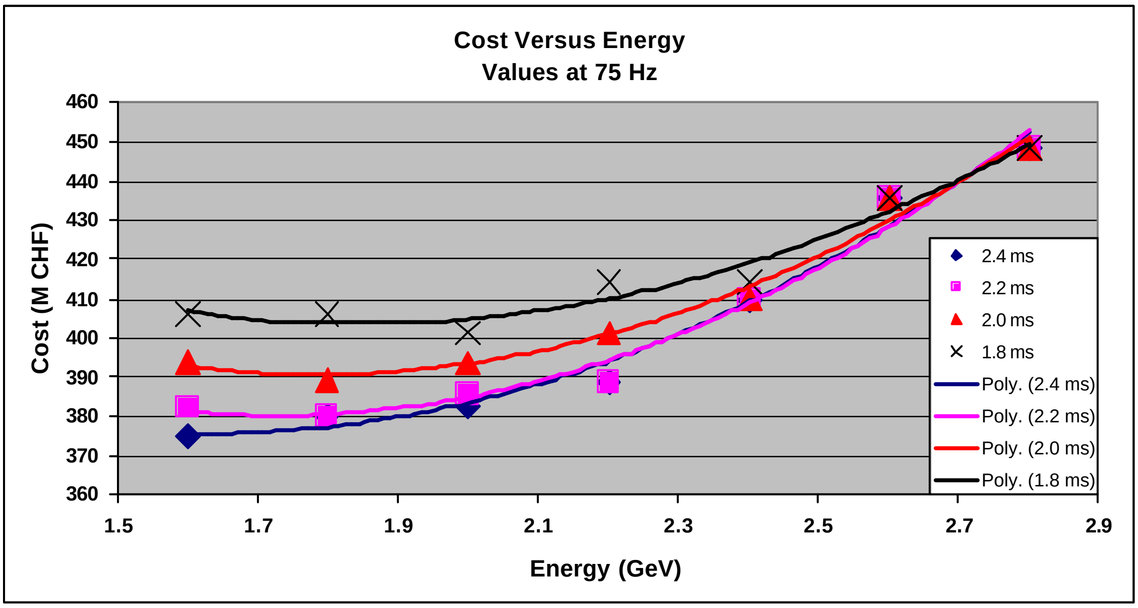


Fig. 3: Results of the cost optimisation studies for different beam pulse lengths at 75 Hz operation. Accelerator costs in M CHF are shown as a function of linac output energy. Note the optimum in costs around 1.8 GeV and that there is a penalty in costs for pulse lengths shorter than 2.2 ms.

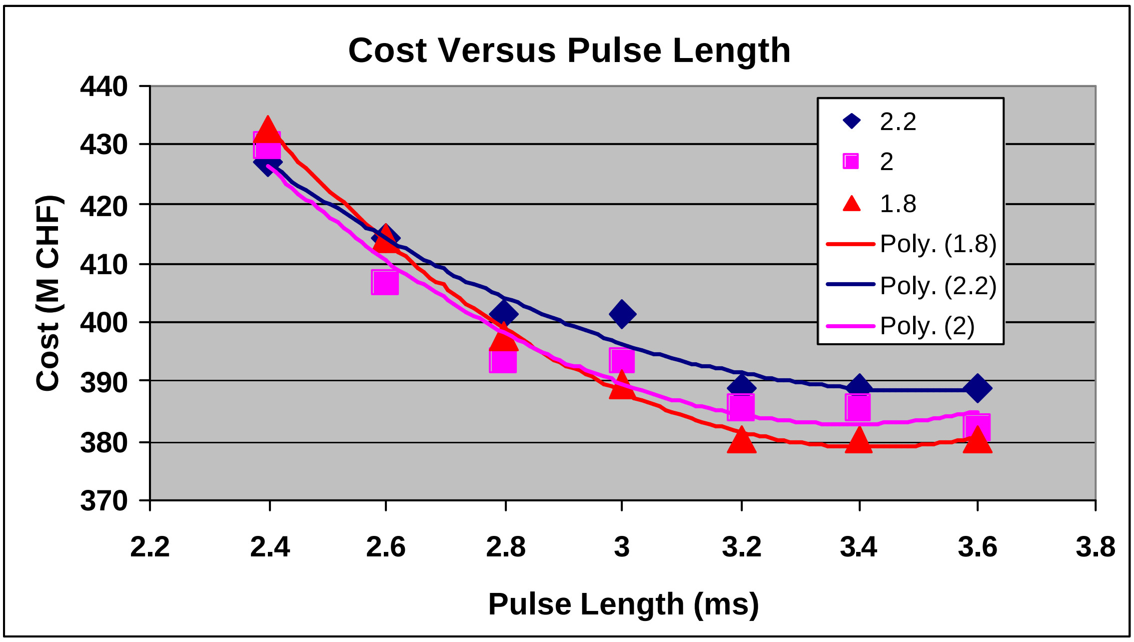


Fig. 4: Costs in M CHF as a function of beam pulse length in ms for the cost optimisation studies at 50 Hz operation. Curves for output energies from 1.8 to 2.2 GeV are shown. All curves show the same general characteristics for pulse lengths less than 2.8 ms. The shoulder in the curve starts at 2.8 ms indicating no significant advantage for pulse lengths in excess of 3 ms.

Figure 5 gives the average AC power in MW as a function of proton beam energy in GeV. The curve shown for the 2.8 ms 50 Hz case is linear as expected, showing that the quantization of the elements used in this study is satisfactory in a general sense. There is a slight penalty to be paid for lower energy designs requiring higher beam currents in the linac, a penalty that is almost 1.6 MW per GeV decrease in linac output energy.

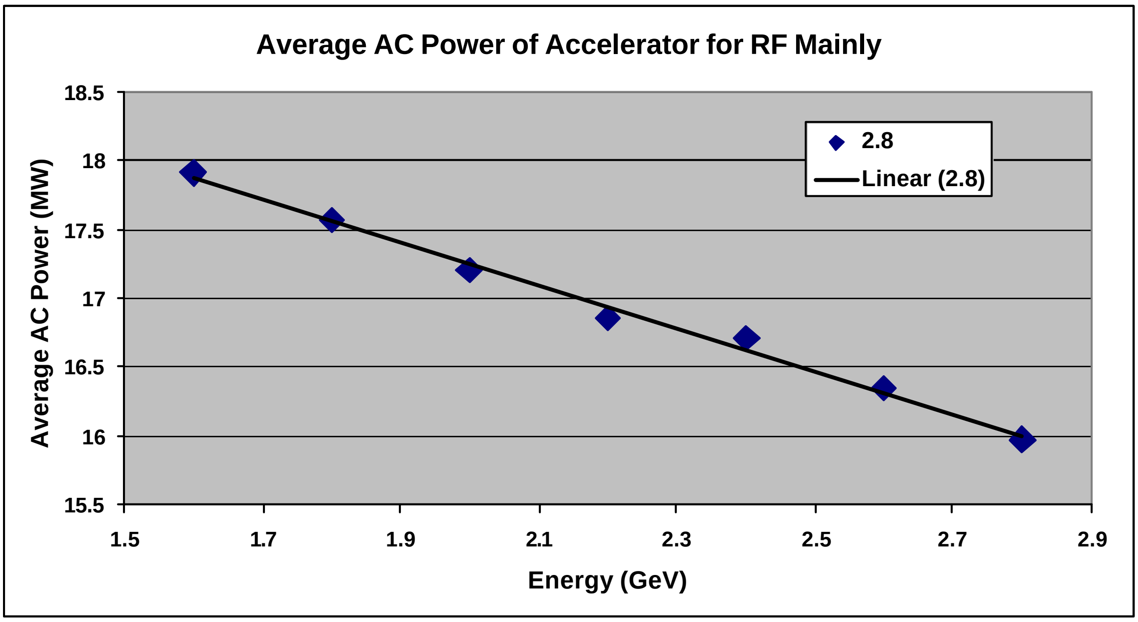


Fig. 5: Results of estimation of AC power requirements in MW for the 2.8 ms, 50 Hz case.

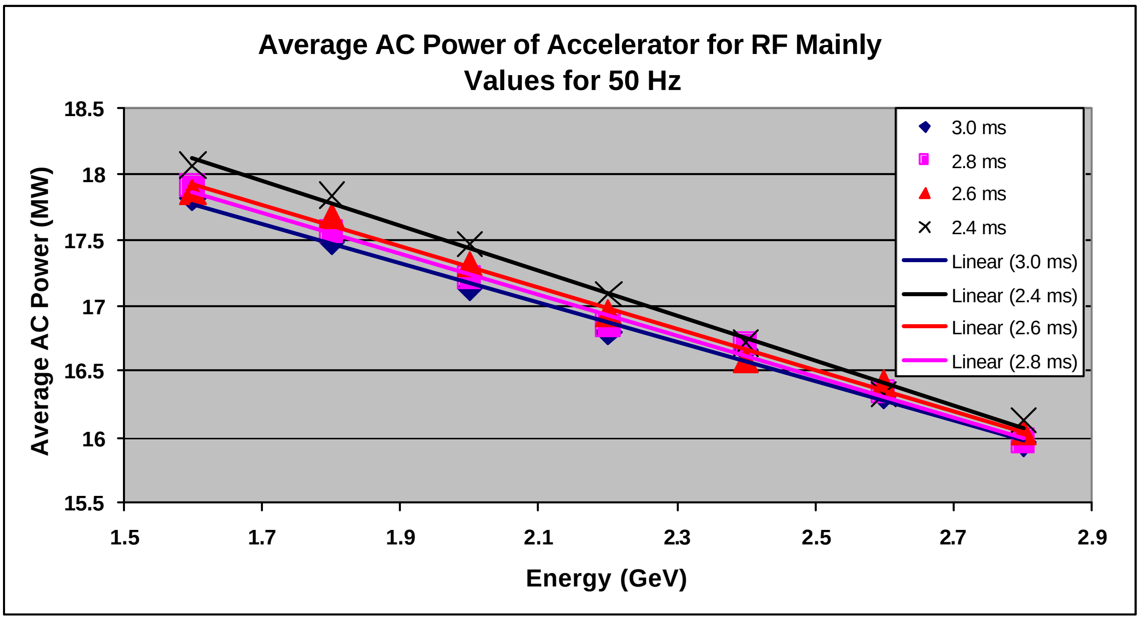


Fig. 6: Results of estimation of AC power requirements in MW for the different beam pulse cases showing the trends that indicate a shorter pulse with higher beam current requires more AC power.

Figure 6 shows the changes in trends for AC power requirements for different beam pulse lengths for 50 Hz operation. Note that shorter pulse lengths require more AC power, an effect associated with higher beam currents in the beam pulse and a constraint for the NC elements of the linac.

5. SUMMARY AND CONCLUSIONS

Optimisation studies showed that a 2.2 GeV, 2.8 ms, 50 Hz design is close to the optimum choice for a SPL under the constraints imposed in this study. A relatively small saving of about 6 M CHF can be realized by reducing the energy from 2.2 GeV to 2.0 GeV. Costs presented here are only estimates and should not be used to determine an absolute cost value for SPL; the data is useful for investigating trends only. Estimates are at best good to 20 % in absolute value. The change to 50 Hz from 75 Hz, although important for linking to other components tied to the natural AC cycle, has an estimated cost penalty of 10 M CHF, an insignificant penalty.

There is a significant cost penalty incurred in a linac design for beam pulse lengths less than 2.8 ms at 50 Hz and less than 2.2 ms at 75 Hz. Although costs are similar for longer beam pulse lengths, linac designs for longer pulses should be avoided because the longer the pulse, the more difficult it is to obtain excellent ‘flat-top’ stability during the pulse. There is no advantage in making the pulse shorter than 2.8 ms from the point of view of enhanced performance relative to field breakdown. Once the rf pulse length is greater than 1.3 ms, the linac is in an operating regime where high rf field effects [4] similar to that of 100 % duty factor linacs will be experienced.

The routine “SPL Cost Optimiser” shown in Appendix A can be used for other studies with other parameters, and should be used with the HARP [5] data when it becomes available to verify conclusions presented in this report.

6. ACKNOWLEDGEMENTS

The author thanks CERN for providing an opportunity to complete this study. Discussions with Maurizio Vretenar and Roland Garoby were very useful in determining limitations and opportunities. Work supported by CERN and US Department of Energy.

7. REFERENCES

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[4] **S. O. Schriber**, “Factors Limiting the Operation of Structures under High Gradient”, in *Proceedings of 1986 Linear Accelerator Conference*, Stanford, California, SLAC publication SLAC-303, p. 591.

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APPENDIX A

Copies of worksheets from the workbook for the routine "SPL Cost Optimiser" are provided in this appendix, in order to indicate parameter selections and program options. The first worksheet called "Assumptions and Input" contains input parameters and a description of the program assumptions and operations. The following three worksheets determine linac designs, check on design constraints and estimate costs for the requested designs.

A.1. 'Assumptions and Operation' worksheet

Power at 2.2GeV (MW)	4		Chopping Efficiency			0.6		SC Power Margin			0.75
Repetition Rate (Hz)	50		Beam capture source			0.85		NC Power Margin			0.8
Pulse Length (ms)	2.8		SC effective accel. space			0.8		RF Tube Ops. Efficiency			0.6
								AC to DC plus supplies			0.9
Accelerator Sections	Output Energy (GeV)	Active Length (m)	Inactive Length (m)	Total Length (m)	Stable Phase (deg.)	TTF	Max. Grad. (MV/m)	Initial Section Number	Section Structure Power	No. of RF Drives	RF Drive (MW)
SC4 (b=1.0)	2.2	11.285	1.93722	357	15	0.6366	7.5	27		18	1
SC3 (b=0.8)	1.08	11.285	1.465	153	15	0.6366	9	12		12	1
SC2 (b=0.7)	0.389	8.916	1.084	80	20	0.6366	5	8		32	0.1
SC1 (b=0.52)	0.237	5.92	1.29429	101	25	0.6366	3.5	14		42	0.1
CCDTL	0.12	7.7333		69.6	30	0.75	2.5	9	5.978	9	1
DTL2	0.018	4.3	0.8	5.1	32	0.75	2.5	1	0.839263	1	1
DTL1	0.012	3.3	0.8	4.1	36	0.75	2.5	1	0.639737	1	1
RFQ2	0.007	3.9	0.1	4	30		2.5	1	0.456	1	1
Choppers	0.003	6		6	30		2.5	5	0.3	5	0.1
RFQ1	0.003	2.6	0.4	3	30		2.5	1	0.327495	1	1
Source/Injector LEBT	4.5E-05	3		3							
Totals				**785.8**						**122**	**50.9**
Use new HARP data for pion production?	**New HARP data =**			**1**		Value for using which pion data in this spreadsheet			0		
	Old data =			**0**							
HARP data											
Proton energy (GeV)	**1.6**	**1.8**	**2**	**2.2**	**2.4**	**2.6**	**2.8**				
Pions/p/GeV in bin											
(80<E<450 MeV)	**(Insert data above for appropriate energy of proton beam)**										

Assumptions and Operation.

* Assumed best available data for the pion production per proton per GeV. Beam power for the required muon flux was normalized to 4 MW at 2.2 GeV. Better data from the HARP experiment can be incorporated when available.

* Assumed 44 cryostats available from CERN as well as 44 klystron stands and tubes.

* Other initial constraints:

- Energy from the injector 0.045 MeV, energy from RFQ1 3 MeV with one 1 MW tube, chopper with five 0.1 tetrodes, energy from RFQ2 7 MeV with one 1 MW klystron, energy from DTL1 12 MeV with one 1 MW klystron, energy from DTL2 18 MeV with one 1 MW klystron, energy from CCDTL 120 MeV with nine 1 MW klystrons driving 9 systems of tanks, energy from SC1 (based on 5.92 m cryostat with three cavities as a module) 237 MeV with 42 tetrodes driving 14 cryostats, energy from SC2 (based on 8.916 m cryostat with four cavities as a module) 389 MeV with 32 tetrodes driving 8 cryostats, energy from SC3 (based on 11.285 m cryostat with four cavities as a module) 1080 MeV with 12 klystrons driving 12 cryostats, and energy from SC4 (based on 11.285 m cryostat with three cavities as a module) final energy with two klystrons driving 3 cryostats.
- Module sizes used in calculations, hence a large quantum step in some cases:
  - DTL1: length adjusted to meet gradient and then power requirements.
  - DTL2: length adjusted to meet gradient and then power requirements.
  - CCDTL: each system driven by one klystron.
  - SC1: cryostat with three cavities driven by three tetrodes.
  - SC2: cryostat with four cavities driven by four tetrodes.
  - SC3: cryostat with four cavities driven by one klystron.
  - SC4: three cryostats (each with three cavities) driven by two klystrons.

* Analysis steps are as follows

1. Using input variables on first sheet and pion production values on second sheet, beam currents at the assumed duty cycle are determined on sheet four. These values are used in the first iterations on sheet two to work out the system parameters based on the assumed linac of sheet one. Rf powers and gradients are determined for the input system. Sheet three takes these values and checks for gradients within the acceptable maximum value. If gradient is exceeded, the particular element is made longer (by a unit size limitation) and new values are determined. The rf power to each element is then checked. If this exceeds the possible delivery level from the rf source, the particular element is made longer (by a unit size limitation and new values are determined. These new values are listed in the second set of rf numbers on sheet two. From these rf needs, the ac power is determined on sheet two using fill times

and efficiencies for each rf system.

2. From the system parameters determined on sheet two, the costs of the linac are determined on sheet four using input data for each element as listed on the sheet.

* Input parameters highlighted in yellow, parameters from another sheet highlighted in green, parameters from the same sheet highlighted in blue and important numbers highlighted in rose.

* Gradients were used to determine the number of cryo modules for the four betas, the number of CCDTLs, and the length of the two DTLs plus two RFQs. If within gradient limits, the DTLs and the RFQs were left the same. Following this check, a check on the power available for each unit was checked to see if this met the tube requirements. If not, the number of units or the length was increased again. Then the power, and the number of elements and their length were determined.

* Initial costs and lengths were obtained from the green book on the basis of 75 Hz operation. The input screen on this sheet allows a change of basic parameters such as nominal power (MW) at 2.2 GeV, pulse length (ms) and repetition rate (Hz).

* Component assumptions are given in the adjacent input list for the different sections. The CCDTL is simplified into 9 units on average with an average stable phase of -30 degrees (based on -35 to -25). The average stable phase for the DTLs is -32 and -36 on the basis of averaging the design change from -38 to -30. The TTF for the SC tanks is assumed to be the simple $2/\pi$ for a pillbox cavity while TTF for the DTL and CCDTL tanks is assumed to be a reasonable value of 0.75.

* Lengths, stable phases for the SC come from table 4.5 and 4.6 of Green book, not the lengths for the SC given in table 3.3. Assumed an 80% useable factor for the SC cavity within the cryostat length -- to determine average gradients for the cavities.

* Structure power for the NC systems at average operating gradients and average number of CCDTL tanks was estimated from the total power in the green book minus beam power. Assumed the powers to each DTL tank were equal per unit length.

* Margins allowed for the rf power drive to the cavities allowing for control, waveguide losses, coupling mismatches (VSWR>1), circuit components and some leverage are 75 % for the SC case and 80 % for the NC case. Because the tubes are not run at full saturation it is assumed that they are 60 % efficient. The AC to DC and power supplies required is assumed to be 90 % efficient.

* To first order when the NC length is changed because of constraints, procedure was to keep section output energy fixed and power times length a constant.

Costs

Costs were obtained from data provided by Maurizio Vretenar for the 75 Hz case. Changes and uses of this data are explained below.

* For ion source currents less than 75 mA only one source, RFQ, LEBT and chopper were included. Higher currents (>75 mA) would double the numbers and the double the costs in the three rows covering these costs. Currents in excess of 150 mA were not considered an option.

* DTL1 and DTL2 were costed together with the formula: Cost (M CHF) = 0.5 + 0.35 * [DTL length (m)], on the basis of the cost breakdowns provided.

* CCDTL was costed on the basis of the number of tanks driven by one rf system: Cost (M CHF) = 0.5 * Number.

* Quads with power supplies were costed on the basis of the 9 CCDTL systems in the reference 75 Hz case and the number needed for the scenario investigated: Cost (M CHF) = 10 / 9 * Number. It was assumed that this method looked after the DTL needs as well.

* Tetrode amplifiers were costed on the basis of the number needed plus 10% for spares: Cost (M CHF) = 0.2525 * (Number + 10%).

* Klystron amplifiers were costed on the basis of 25 M being the cost for 44 units with spares and numbers less than this would be costed on a proportional basis: Cost (M CHF) = 25 * Number / 44. A premium for klystron amplifiers in excess of 44 was based on 1.615 M per item: Cost (M CHF) = 25 + 1.615 * (Number - 44). The 1.615 M is based on 2.5 / 6 M for the power supply, 0.23 for waveguides, etc., 0.4 for the klystron and 25/44 for pulsing systems including capacitor bank.

* Cavity servos and beam phase monitoring was costed on the basis of the number of rf drivers (tetrodes and klystrons) required as compared to the number in the reference 75 Hz case: Cost (M CHF) = 3 * Number / 122.

* Spare cavities for all of the betas was assumed to be the same at 10 M, as indicated in a cost estimate given M.V.

* SC4 b = 1.0 cryostat unit costs were estimated on the basis of 27 costing 4.8 M. As long as the number required was less than 45, costs would be given by: Cost (M CHF) = 4.8 / 27 * Number. Above 44, the premium cost per cryostat (done in units of three) was 2 M per cryostat.

‘Assumptions and Operation’ worksheet continued 2

* SC3 b = 0.8 cryostat unit costs were estimated on the basis of how many LEP cryostats were left from the 44 total minus the b=1.0 requirements. These were costed at: Cost (M CHF) = 0.6 * Number. Others that couldn't use the LEP cryostats were costed at 2 M per cryostat.

* SC2 b = 0.7 cryostat unit costs were estimated on the basis of 2 M per cryostat: Cost (M CHF) = 2 * Number.

* SC1 b = 0.52 cryostat unit costs were estimated on the basis of 27 M for 14 cryostats: Cost (M CHF) = 27 / 14 * Number.

* Beam instrumentation was estimated on the basis of length using the 6.3 M estimate for the 800 m original length: Cost (M CHF) = 6.3 * [Accelerator Length (m)] / 800.

* Controls were estimated by adding all of the components, other than controls and the contingency. Controls were 10% of this total.

* Civil engineering was estimated using the base cost of 31.23 M (75.65 minus the linac and klystron tunnels, etc.) plus 25 % of the remaining 44.42 M as a base cost. The remaining 75 % of the 44.42 M was allocated on the basis of accelerator length assuming the 75Hz basis of 800 m: Cost (M CHF) = 31.23 + 0.25 * 44.42 + 0.75 * 44.42 * [Accelerator Length (m)] / 800.

* Cooling and ventilation was estimated on the basis of 95 % of the 10.02 M as a base cost and the remaining 5 % of 10.02 M on the basis of length relative to the 800 m original length: Cost (M CHF) = 0.95 * 10.02 + 0.05 * 10.02 * [Accelerator Length (m)] / 800.

* Controlled access and alarms, transfer lines, dumps, radiation monitoring, PS injection, ISOLDE injection, land acquisition and cavities cold test were based on the original 75 Hz estimates.

* Electricity was estimated on the basis of 95 % of the 14.627 M as a base cost and the remaining 5 % of 14.627 M on the basis of length relative to the 800 m original length: Cost (M CHF) = 0.95 * 14.627 + 0.05 * 14.627 * [Accelerator Length (m)] / 800.

* Cryogen plant was estimated on the basis of 34.5 M as a base cost and the remaining 5 M for warm piping and He transfer lines on the basis of length relative to the 800 m original length: Cost (M CHF) = 34.5 + 5 * [Accelerator Length (m)] / 800.

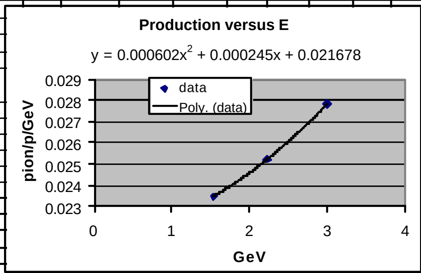
* Vacuum was estimated on the basis of length using the 8 M estimate for the 800 m original length: Cost (M CHF) = 8 * [Accelerator Length (m)] / 800.

A.2. ‘Data manipulation’ worksheet.

This worksheet begins the process of linac design, and lists the final design parameters used to determine AC power requirements.

Injector E (GeV) Output	RFQ1 Out	RFQ2 Out	DTL1 Out	DTL2 Out	CCDTL Out	SC1 Out	SC2 Out	SC3 Out	SC4 Out	Data Range		Prod and E Values		Measure Prod and E	
0.000045	0.003	0.007	0.012	0.018	0.12	0.237	0.389	1.08	END	0.02	0	0.0235	1.53846	8	10
	Pion Production									0.03	4	0.0252	2.23077	12	14.5
	Poly Values	0.0006	0.0002	0.0217					Green Report RF Power	L (m)		0.0278	3	18	19.5

Linac Output Energy	1.6	1.8	2	2.2	2.4	2.6	2.8	
pions	0.0236	0.0241	0.0246	0.0251	0.02573	0.0264	0.0271	
pions norm.	0.9395	0.9578	0.9779	1	1.02399	1.0499	1.0777	Norm
Total Beam Power (MW)	30.41	29.831	29.216	28.571	27.9021	27.214	26.511	
Beam in SC4 (MW)	9.8833	11.932	13.439	14.545	15.3462	15.91	16.285	
Beam in SC3 (MW)	13.133	11.452	10.094	8.974	8.03348	7.2326	6.5426	
Beam in SC2 (MW)	2.889	2.5191	2.2204	1.974	1.76713	1.591	1.4392	
Beam in SC1 (MW)	2.2237	1.939	1.7092	1.5195	1.36023	1.2246	1.1078	
Beam in CCDTL (MW)	1.9387	1.6904	1.49	1.3247	1.18584	1.0676	0.9658	
Beam in DTL2 (MW)	0.114	0.0994	0.0876	0.0779	0.06976	0.0628	0.0568	
Beam in DTL1 (MW)	0.095	0.0829	0.073	0.0649	0.05813	0.0523	0.0473	
Beam in RFQ2 (MW)	0.076	0.0663	0.0584	0.0519	0.0465	0.0419	0.0379	
Chopper								
Beam in RFQ1 (MW)	0.0562	0.049	0.0432	0.0384	0.03435	0.0309	0.028	
Check	0	0	0	0	0	0	0	



NC TTF	SC Use
0.75	0.8

								(MV/m)	S(MW)	L(m)	Power Margin	Gradient Check							SC TTF 0.64 ϕ	Cryo L(m)	Cryo #
RF Power to SC4 (MW)	13.178	15.91	17.919	19.394	20.4615	21.213	21.714	7.5	0		SC	3.4692	4.80345	6.14	7.472	8.806	10.1	11.47	15	11.3	27
RF Power to SC3 (MW)	17.511	15.269	13.459	11.965	10.7113	9.6434	8.7234	9	0		0.75	10.372	10.3724	10.4	10.37	10.37	10.4	10.37	15	11.3	12
RF Power to SC2 (MW)	3.852	3.3588	2.9606	2.632	2.35618	2.1213	1.9189	5	0		NC	4.4527	4.45274	4.45	4.453	4.453	4.45	4.453	20	8.92	8
RF Power to SC1 (MW)	2.965	2.5854	2.2789	2.026	1.81364	1.6328	1.477	3.5	0		0.8	3.0584	3.05837	3.06	3.058	3.058	3.06	3.058	25	5.92	14
RF Power to CCDTL (MW)	9.8958	9.5855	9.335	9.1283	8.9548	8.807	8.6797	2.5	5.978	7.73		2.2563	2.25631	2.26	2.256	2.256	2.26	2.256	30		9
RF Power to DTL2 (MW)	1.1916	1.1734	1.1586	1.1465	1.13627	1.1276	1.1201	2.5	0.83926	4.3		2.1938	2.19382	2.19	2.194	2.194	2.19	2.194	32		1
RF Power to DTL1 (MW)	0.9185	0.9033	0.891	0.8808	0.87233	0.8651	0.8588	2.5	0.63974	3.3		2.4971	2.49711	2.5	2.497	2.497	2.5	2.497	36		1
RF Power to RFQ2 (MW)	0.665	0.6529	0.643	0.6349	0.62813	0.6223	0.6173	2.5	0.456	3.9		1.8603	1.86031	1.86	1.86	1.86	1.86	1.86	30		1
RF Power to Chopper	0.375	0.375	0.375	0.375	0.375	0.375	0.375	2.5	0.3	6		0	0	0	0	0	0	0	30		5
RF Power to RFQ1 (MW)	0.4796	0.4706	0.4633	0.4573	0.45231	0.448	0.4443	2.5	0.3275	2.6		2.0615	2.06145	2.06	2.061	2.061	2.06	2.061	30		1
Total RF Power (MW)	51.031	50.284	49.484	48.64	47.7615	46.855	45.929					2.8351									

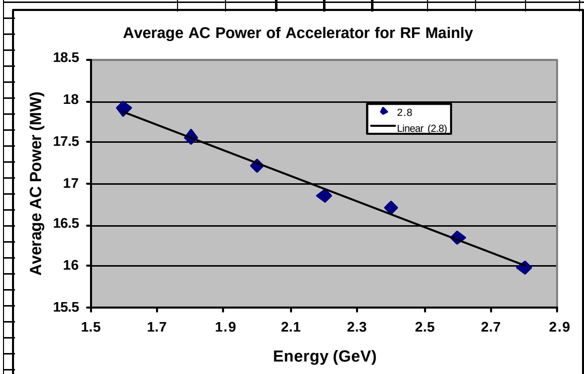
Information to following sheet for analysis of gradient and power availability

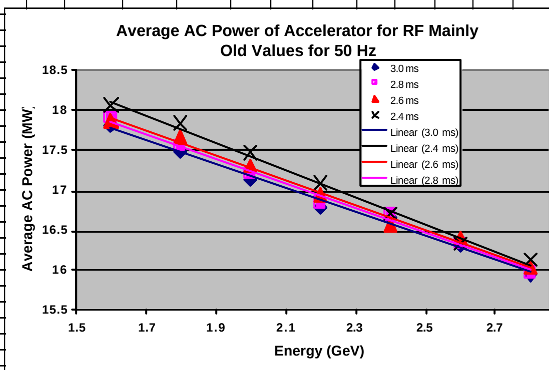
Information from following sheet

								(MV/m)	S(MW)	L(m)	Margin	MW	#
RF Power to SC4 (MW)	13.178	15.91	17.919	19.394	20.4615	21.213	21.714	7.5	0	0	SC	1	18
RF Power to SC3 (MW)	17.511	15.269	13.459	11.965	10.7113	9.6434	8.7234	9	0	0	0.75	1	12
RF Power to SC2 (MW)	3.852	3.3588	2.9606	2.632	2.35618	2.1213	1.9189	5	0	0	NC	0.1	32
RF Power to SC1 (MW)	2.965	2.5854	2.2789	2.026	1.81364	1.6328	1.477	3.5	0	0	0.8	0.1	42
RF Power to CCDTL (MW)	9.1486	8.8383	8.5878	8.3811	8.9548	8.807	8.6797	2.5	5.978	7.73		1	9
RF Power to DTL2 (MW)	0.9889	0.9865	0.985	0.9841	0.98358	0.9833	0.9832	2.5	0.83926	4.3		1	1
RF Power to DTL1 (MW)	0.9185	0.9033	0.891	0.8808	0.87233	0.8651	0.8588	2.5	0.63974	3.3		1	1
RF Power to RFQ2 (MW)	0.665	0.6529	0.643	0.6349	0.62813	0.6223	0.6173	2.5	0.456	3.9		1	1
RF Power to Chopper	0.375	0.375	0.375	0.375	0.375	0.375	0.375	2.5	0.3	6		0.1	5
RF Power to RFQ1 (MW)	0.4796	0.4706	0.4633	0.4573	0.45231	0.448	0.4443	2.5	0.3275	2.6		1	1

Total RF Power (MW)	50.081	49.35	48.563	47.731	47.6088	46.711	45.792		Fill time (ms)	AC to DC, etc.
Operation Average										
AC Power to SC4 (MW)	4.7403	5.7232	6.446	6.9764	7.36047	7.6307	7.811		0.9	
AC Power to SC3 (MW)	7.0823	6.1755	5.4434	4.8393	4.33213	3.9002	3.5281		1.36	0.9
AC Power to SC2 (MW)	1.4718	1.2833	1.1312	1.0057	0.90026	0.8105	0.7332		1.13	Tube Eff.
AC Power to SC1 (MW)	1.0666	0.93	0.8198	0.7288	0.65241	0.5874	0.5313		0.9	0.6
AC Power to CCDTL (MW)	2.5794	2.4919	2.4213	2.363	2.52476	2.4831	2.4472		0.1	
AC Power to DTL2 (MW)	0.2788	0.2781	0.2777	0.2775	0.27732	0.2772	0.2772		0.1	
AC Power to DTL1 (MW)	0.259	0.2547	0.2512	0.2483	0.24595	0.2439	0.2421		0.1	
AC Power to RFQ2 (MW)	0.1875	0.1841	0.1813	0.179	0.1771	0.1755	0.1741		0.1	
AC Power to Chopper	0.1057	0.1057	0.1057	0.1057	0.10573	0.1057	0.1057		0.1	
AC Power to RFQ1 (MW)	0.1352	0.1327	0.1306	0.1289	0.12753	0.1263	0.1253		0.1	
Total AC Power (MW)	17.907	17.559	17.208	16.853	16.7036	16.341	15.975	2.8		

50 Hz Old Values								
	17.82	17.482	17.14	16.793	16.6672	16.312	15.954	3
	17.907	17.559	17.208	16.853	16.7036	16.341	15.975	2.8
	17.876	17.678	17.316	16.951	16.5813	16.405	16.031	2.6
	18.071	17.848	17.474	17.097	16.7163	16.333	16.13	2.4





A.3. 'Field and RF Check' worksheet.

This worksheet analyses the initial linac design, iterates the design on the basis of allowed structure gradient, and then iterates the design based on rf power limitations delivered to a cavity.

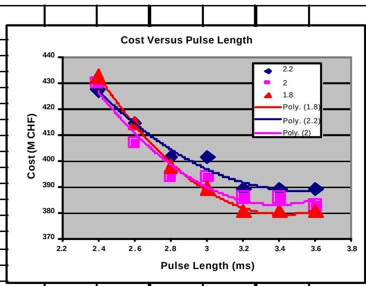
Injector E (GeV) Output	RFQ1 Out	RFQ2 Out	DTL1 Out	DTL2 Out	CCDTL Out	SC1 Out	SC2 Out	SC3 Out	SC4 Out															
0.000045	0.003	0.007	0.012	0.018	0.12	0.237	0.389	1.08	END									NC	0.75	0.8	Use			
																			TTF	Cryo	Cryo	RF	Ratio	RF
Linac Output Energy	1.6	1.8	2	2.2	2.4	2.6	2.8	(MV/m)	S(MW)	L(m)	Power	Gradient Check							0.637	L(m)	#	#	RF/Cr	Size
											Margin								ϕ					(MW)
RF Power to SC4 (MW)	13.18	15.91	17.92	19.39	20.46	21.21	21.71	7.5	0	0	SC	3.47	4.8	6.14	7.47	8.81	10.1	11.5	15	11.3	27	18	0.667	1
RF Power to SC3 (MW)	17.51	15.27	13.46	11.97	10.71	9.643	8.723	9	0	0	0.75	10.4	10.4	10.4	10.4	10.4	10.4	10.4	15	11.3	12	12	1	1
RF Power to SC2 (MW)	3.852	3.359	2.961	2.632	2.356	2.121	1.919	5	0	0	NC	4.45	4.45	4.45	4.45	4.45	4.45	4.45	20	8.92	8	32	4	0.1
RF Power to SC1 (MW)	2.965	2.585	2.279	2.026	1.814	1.633	1.477	3.5	0	0	0.8	3.06	3.06	3.06	3.06	3.06	3.06	3.06	25	5.92	14	42	3	0.1
RF Power to CCDTL (MW)	9.896	9.586	9.335	9.128	8.955	8.807	8.68	2.5	5.978	7.73	0	2.26	2.26	2.26	2.26	2.26	2.26	2.26	30		9	9	1	1
RF Power to DTL2 (MW)	1.192	1.173	1.159	1.146	1.136	1.128	1.12	2.5	0.839	4.3	0	2.19	2.19	2.19	2.19	2.19	2.19	2.19	32		1	1	1	1
RF Power to DTL1 (MW)	0.918	0.903	0.891	0.881	0.872	0.865	0.859	2.5	0.64	3.3	0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	36		1	1	1	1
RF Power to RFQ2 (MW)	0.665	0.653	0.643	0.635	0.628	0.622	0.617	2.5	0.456	3.9	0	1.86	1.86	1.86	1.86	1.86	1.86	1.86	30		1	1	1	1
RF Power to Chopper	0.375	0.375	0.375	0.375	0.375	0.375	0.375	2.5	0.3	6	0	0	0	0	0	0	0	0	30		5	5	1	0.1
RF Power to RFQ1 (MW)	0.48	0.471	0.463	0.457	0.452	0.448	0.444	2.5	0.327	2.6	0	2.06	2.06	2.06	2.06	2.06	2.06	2.06	30		1	1	1	1
Total RF Power (MW)	51.03	50.28	49.48	48.64	47.76	46.86	45.93	0	0	0	0													
												System Numbers/Lengths and Gradients												
RF Power to SC4 (MW)	13.18	15.91	17.92	19.39	20.46	21.21	21.71					15	18	24	27	33	39	42	Number					
Power/Unit	1.318	1.326	1.12	1.077	0.93	0.816	0.775					6.24	7.21	6.9	7.47	7.21	7.02	7.38	Gradient					
RF Power to SC3 (MW)	17.51	15.27	13.46	11.97	10.71	9.643	8.723					14	14	14	14	14	14	14	Number					
Power/Unit	1.251	1.091	0.961	0.855	0.765	0.689	0.623					8.89	8.89	8.89	8.89	8.89	8.89	8.89	Gradient					
RF Power to SC2 (MW)	3.852	3.359	2.961	2.632	2.356	2.121	1.919					8	8	8	8	8	8	8	Number					
Power/Unit	0.12	0.105	0.093	0.082	0.074	0.066	0.06					4.45	4.45	4.45	4.45	4.45	4.45	4.45	Gradient					
RF Power to SC1 (MW)	2.965	2.585	2.279	2.026	1.814	1.633	1.477					13	13	13	13	13	13	13	Number					
Power/Unit	0.076	0.066	0.058	0.052	0.047	0.042	0.038					3.29	3.29	3.29	3.29	3.29	3.29	3.29	Gradient					
RF Power to CCDTL (MW)	9.896	9.586	9.335	9.128	8.955	8.807	8.68					9	9	9	9	9	9	9	Number					
Power/Unit	1.1	1.065	1.037	1.014	0.995	0.979	0.964					2.26	2.26	2.26	2.26	2.26	2.26	2.26	Gradient					
RF Power to DTL2 (MW)	1.192	1.173	1.159	1.146	1.136	1.128	1.12					4.3	4.3	4.3	4.3	4.3	4.3	4.3	Length					
Power/Unit	1.192	1.173	1.159	1.146	1.136	1.128	1.12					2.19	2.19	2.19	2.19	2.19	2.19	2.19	Gradient					
RF Power to DTL1 (MW)	0.918	0.903	0.891	0.881	0.872	0.865	0.859					3.3	3.3	3.3	3.3	3.3	3.3	3.3	Length					
Power/Unit	0.918	0.903	0.891	0.881	0.872	0.865	0.859					2.5	2.5	2.5	2.5	2.5	2.5	2.5	Gradient					
RF Power to RFQ2 (MW)	0.665	0.653	0.643	0.635	0.628	0.622	0.617					3.9	3.9	3.9	3.9	3.9	3.9	3.9	Length					
Power/Unit	0.665	0.653	0.643	0.635	0.628	0.622	0.617	P/unit				1.58	1.58	1.58	1.58	1.58	1.58	1.58	Gradient					
RF Power to Chopper	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.075				6	6	6	6	6	6	6	Length					
RF Power to RFQ1 (MW)	0.48	0.471	0.463	0.457	0.452	0.448	0.444					2.6	2.6	2.6	2.6	2.6	2.6	2.6	Length					
Power/Unit	0.48	0.471	0.463	0.457	0.452	0.448	0.444					1.75	1.75	1.75	1.75	1.75	1.75	1.75	Gradient					
				Ensure rf power OK per system																				
												System Numbers/Lengths and Gradients												
RF Power to SC4 (MW)	13.18	15.91	17.92	19.39	20.46	21.21	21.71					21	24	27	30	33	39	42	Number					
Power/Unit	0.941	0.994	0.996	0.97	0.93	0.816	0.775					4.46	5.4	6.14	6.72	7.21	7.02	7.38	Gradient					
RF Power to SC3 (MW)	17.51	15.27	13.46	11.97	10.71	9.643	8.723					18	16	14	14	14	14	14	Number					
Power/Unit	0.973	0.954	0.961	0.855	0.765	0.689	0.623					6.91	7.78	8.89	8.89	8.89	8.89	8.89	Gradient					
RF Power to SC2 (MW)	3.852	3.359	2.961	2.632	2.356	2.121	1.919					10	9	8	8	8	8	8	Number					
Power/Unit	0.096	0.093	0.093	0.082	0.074	0.066	0.06					3.56	3.96	4.45	4.45	4.45	4.45	4.45	Gradient					
RF Power to SC1 (MW)	2.965	2.585	2.279	2.026	1.814	1.633	1.477					13	13	13	13	13	13	13	Number					
Power/Unit	0.076	0.066	0.058	0.052	0.047	0.042	0.038					3.29	3.29	3.29	3.29	3.29	3.29	3.29	Gradient					
RF Power to CCDTL (MW)	9.149	8.838	8.588	8.381	8.955	8.807	8.68					10	10	10	10	9	9	9	Number					
Power/Unit	0.915	0.884	0.859	0.838	0.995	0.979	0.964					2.03	2.03	2.03	2.03	2.26	2.26	2.26	Gradient					
RF Power to DTL2 (MW)	0.989	0.987	0.985	0.984	0.984	0.983	0.983					5.33	5.23	5.15	5.09	5.03	4.99	4.95	Length					
Power/Unit	0.989	0.987	0.985	0.984	0.984	0.983	0.983					1.77	1.8	1.83	1.85	1.87	1.89	1.91	Gradient					
RF Power to DTL1 (MW)	0.918	0.903	0.891	0.881	0.872	0.865	0.859					3.3	3.3	3.3	3.3	3.3	3.3	3.3	Length					
Power/Unit	0.918	0.903	0.891	0.881	0.872	0.865	0.859					2.5	2.5	2.5	2.5	2.5	2.5	2.5	Gradient					
RF Power to RFQ2 (MW)	0.665	0.653	0.643	0.635	0.628	0.622	0.617					3.9	3.9	3.9	3.9	3.9	3.9	3.9	Length					
Power/Unit	0.665	0.653	0.643	0.635	0.628	0.622	0.617	P/unit				1.58	1.58	1.58	1.58	1.58	1.58	1.58	Gradient					
RF Power to Chopper	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.075				6	6	6	6	6	6	6	Length					
RF Power to RFQ1 (MW)	0.48	0.471	0.463	0.457	0.452	0.448	0.444					2.6	2.6	2.6	2.6	2.6	2.6	2.6	Length					
Power/Unit	0.48	0.471	0.463	0.457	0.452	0.448	0.444					1.75	1.75	1.75	1.75	1.75	1.75	1.75	Gradient					
Total RF (MW)	50.08	49.35	48.56	47.73	47.61	46.71	45.79																	
No. of 1 MW Klystrons	46	46	46	48	49	53	55																	
No. of 0.1 MW Tetrodes	84	80	76	76	76	76	76																	
No. of LEP Cryostats	39	40	41	44	47	53	56																	
Length (m)	801.7	805.8	809.8	849.4	881.3	960.6	1000		Less 3 m length for the ion source & LEBT															
Total RF Reserve	54.4	54	53.6	55.6	56.6	60.6	62.6																	
Efficiency of RF	0.921	0.914	0.906	0.858	0.841	0.771	0.731																	

A.4. 'Cost' worksheet.

This final worksheet analyses beam current requirements in the pulse, based on pion production data from the first worksheet and used in the two previous worksheets. This worksheet also provides the cost analysis for the linacs designed in the previous worksheets.

Assume:
*** 60% overall [62.5% chopping efficiency (5 our of 8 bunches), but only 140 out of 146 bunches for kicker giving 60% overall].**
*** 85% ion source capture.**
*** 14% beam duty cycle.**
*** Single injector, if ion source I < 75 mA.**
*** RFQ1 to 3, RFQ2 to 7, DTL to 120, SC1-3 to 1080, SC4 rest.**

Chop Eff.	Source Capture
0.6	0.85



Beam Power (MW)	4	4	4	4	4	4	4
Pulse (Hz)	50	50	50	50	50	50	50
Beam Pulse Length (ms)	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Output Energy (GeV)	1.6	1.8	2	2.2	2.4	2.6	2.8
Relative pion production (norm. to 1 at 2.2 GeV)	0.94	0.96	0.98	1.00	1.02	1.05	1.08
Average Beam Current in Pulse (mA)	19.0	16.6	14.6	13.0	11.6	10.5	9.5
Peak Beam Current in Pulse (mA)	31.7	27.6	24.3	21.6	19.4	17.4	15.8
Ion Source Output (mA)	37.3	32.5	28.6	25.5	22.8	20.5	18.6
Average Beam Power in pulse (MW)	30.4	29.8	29.2	28.6	27.9	27.2	26.5
Beam Power normalized to pion production (MW)	4.3	4.2	4.1	4.0	3.9	3.8	3.7
Comments							

	Costs in MCHF								REFERENCE					
									75 Hz Unit	CHF/m	CHF/ unit	CHF/ extra		
H^- Source	0.6	0.6	0.6	0.6	0.6	0.6	0.6		0.6					
RFQs & LEBT	6.0	6.0	6.0	6.0	6.0	6.0	6.0		6.0					
Chopper with high and low power electronics	3.5	3.5	3.5	3.5	3.5	3.5	3.5		3.5					
DTL	4.1	4.0	4.0	4.0	4.0	4.0	3.9		9.0	0.35	0.5			
CCDTL	5.0	5.0	5.0	5.0	4.5	4.5	4.5				0.5			
Quads with power supplies	11.1	11.1	11.1	11.1	10.0	10.0	10.0		10.0					
Tetrode amplifiers (+spares)	23.3	22.2	21.1	21.1	21.1	21.1	21.1		20.0		0.2525		Spares	0.1
Klystron Amplifiers (+ new klystrons)	28.2	28.2	28.2	31.5	33.1	39.5	42.8		25.0		25	1.6148		
Cavities servos and beam phase monitoring	3.2	3.1	3.0	3.0	3.1	3.2	3.2		3.0					
Spare cavities (all betas)	10.0	10.0	10.0	10.0	10.0	10.0	10.0				10			
Beta=1.0 SC4 cavities	3.7	4.3	4.8	5.3	5.9	6.9	7.5		5.0		0.1778	2		
Beta=0.8 SC3 cavities	10.8	9.6	8.4	8.4	12.6	21.0	25.2		55.0		0.6	2		
Beta=0.7 SC2 cavities	20.0	18.0	16.0	16.0	16.0	16.0	16.0				2			
Beta=0.52 SC1 cavities	25.1	25.1	25.1	25.1	25.1	25.1	25.1				1.9286			
Beam instrumentation	6.3	6.3	6.4	6.7	6.9	7.6	7.9		6.3	0.0079				
Controls	33.2	32.9	32.5	33.2	33.9	36.0	37.1		6.0	Use 10% total w/o contingency				0.1
Civil Engineering	75.7	75.9	76.1	77.7	79.0	82.3	84.0		75.7	0.0416	31.23	11.105		
Cooling and ventilation	10.0	10.0	10.0	10.1	10.1	10.1	10.1		10.0	0.0006	9.519			
Controlled access and alarm	1.3	1.3	1.3	1.3	1.3	1.3	1.3		1.3		1.288			
Electricity	14.6	14.6	14.6	14.7	14.7	14.8	14.8		14.6	0.0009	13.896			
Cryogen plant	39.5	39.5	39.6	39.8	40.0	40.5	40.8		40.0	0.0063	34.5			
Vacuum	8.0	8.1	8.1	8.5	8.8	9.6	10.0		8.0	0.01				
Transfer lines (vacuum, magnets, power supplies)	4.0	4.0	4.0	4.0	4.0	4.0	4.0		4.0					
Dumps (2 + 1.5 spare)	1.8	1.8	1.8	1.8	1.8	1.8	1.8		1.8					
Radiation Monitoring	0.5	0.5	0.5	0.5	0.5	0.5	0.5		0.5					
Injection in the PS	4.0	4.0	4.0	4.0	4.0	4.0	4.0		4.0					
Injection in the ISOLDE	0.5	0.5	0.5	0.5	0.5	0.5	0.5		0.5					
Land Acquisition	1.5	1.5	1.5	1.5	1.5	1.5	1.5		1.5					
Cavities cold test (3 bunkers + 5 years duration)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	Pulse	10.0					
10% Contingency	36.6	36.2	35.8	36.5	37.2	39.6	40.8	Length	28.7	0.1				
Total	**402.3**	**397.9**	**393.5**	**401.3**	**409.6**	**435.4**	**448.3**	2.8	**350.0**					
Linac Output Energy (GeV)	**1.6**	**1.8**	**2**	**2.2**	**2.4**	**2.6**	**2.8**	ms						

50 Hz Old Values

375.015	380.286	382.268	388.818	409.565	435.396	448.306	3.6
377.515	380.302	385.578	388.83	409.576	435.406	448.315	3.4
384.715	380.319	385.594	388.844	409.588	435.418	448.325	3.2
393.797	389.398	393.455	401.267	409.602	435.431	448.336	3
402.269	397.867	393.475	401.285	409.619	435.445	448.350	2.8
423.152	414.183	406.785	414.231	427.126	435.462	448.365	2.6
437.076	432.582	429.877	427.181	427.148	440.045	448.383	2.4

75 Hz Old Values

375.015	380.286	382.268	388.818	409.565	435.396	448.306	2.4
382.222	380.31	385.586	388.837	409.582	435.412	448.32	2.2
393.797	389.398	393.455	401.267	409.602	435.431	448.336	2
406.032	405.724	401.33	414.22	414.191	435.453	448.357	1.8